ANALYSIS OF THE BOND BETWEEN NEAR-SURFACE MOUNTED CFRP LAMINATE STRIPS AND CONCRETE

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ABSTRACT

The flexural and the shear resistance of concrete, masonry and timber structures can be efficiently increased using near-surface mounted (NSM) CFRP laminate strips. This technique consists on introducing CFRP laminate strips into grooves made on the cover concrete of the structural elements to be strengthened. Bond behavior of CFRP reinforcement is a key feature, not only for the strengthening efficacy provided by this technique, but also in the structural design. To assess the local bond stress-slip relationship, a numerical strategy was developed taking into account the results obtained in monotonic and cyclic pullout-bending tests that were carried out for this purpose. This relationship was transformed into a bond stress-slip constitutive law for a line interface finite element, used to simulate the concrete-CFRP bond behavior. Important design aspects, like the anchorage length of the CFRP to accomplish the requisites imposed by service and ultimate limit state analysis, can also be determined by the developed model. The experimental and the numerical research are described in this paper.

1 INTRODUCTION

In last years, a strengthening technique based on the Near-Surface Mounted (NSM) of laminate strips of CFRP has been used to increase the load carrying capacity of concrete members (see Figure 1). The term 'near' is used to differentiate this technique of structural strengthening from that using externally-bonded FRP composites (EBR). In the NSM CFRP technique, laminate strips of CFRP are introduced into grooves pre-cut on the concrete cover of the elements to be strengthened that were previously filled with epoxy adhesive. The CFRP has a cross section of about 1.4 mm thick and 10 mm width, while the width and the depth of the groove vary between 3 mm to 5 mm, and 12 mm to 15 mm, respectively.

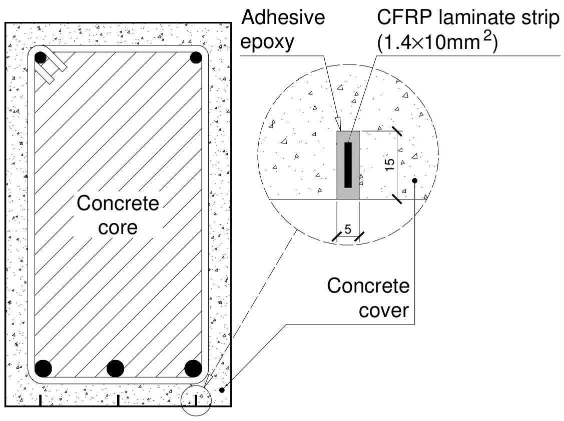

Figure 1: Strengthening technique based on the Near Surface Mounted.

The benefits in terms of load carrying capacity and deformation capacity showed that this is a promising technique for strengthening, not only concrete elements failing in bending (Ferreira [1], Barros and Fortes [2]), but also concrete beams failing in shear (Barros and Dias [3]).

Since bond behavior analysis is a requirement for understanding the stress transfer process between concrete and CFRP, an experimental program of pullout-bending tests was carried out. Using the same groove size and epoxy adhesive, bond behavior is analyzed in order to determine the influences of both bond length and the loading history on the bond behavior (Sena-Cruz et al. [4]).

To define a local bond stress-slip relationship, $\tau - s$, a numerical strategy was developed where the experimental results were taken into account. Based on the methodology used in the bonding of steel bars to concrete, several approaches have been developed to establish a local $\tau - s$ relationship for FRP rods (Larralde and Silva-Rodriguez [5], Malvar [6], Cosenza et al. [7], Focacci et al. [8], De Lorenzis et al. [9]). The method proposed by Focacci et al. [8] was used in the present work, with the necessary adjustments to account the specificities of the present strengthening technique.

The finite element method (FEM) is a powerful tool to simulate the behavior of reinforced concrete structures. Interface elements are adjusted for modeling the bond between concrete and reinforcement (Schellekens [10], Henriques et al. [11], De Lorenzis [12]). However, they have been rarely used in the simulation of the FRP-concrete bonding (Henriques et al. [11], De Lorenzis [12]). In the present paper, the obtained $\tau - s$ relationship was used to define the tangential component of the constitutive law of a line interface element applied in the simulation of the carried out pullout bending tests. The performance of this numerical modeling is analyzed.

2 PULLOUT-BENDING TESTS

To assess the bond behavior between concrete and laminate under monotonic and cyclic loadings, pullout-bending tests were carried out (Sena-Cruz et al. [4]). The test layout adopted (Figure 2) is similar to the one proposed by RILEM for assessing the bond characteristics of conventional steel rods (RILEM [13]). The pullout force at the laminate, and the slip at the free (s_f) and loaded (s_l) ends were measured. The influences of the bond length (Lb) and the load history were analyzed through tests with Lb=60, 90 and 120 mm and through monotonic (M) and cyclic tests (C1 - one cycle of loading/unloading at different slip levels; C10 - ten cycles of loading/unloading at a fixed load level).

Figure 3 includes the typical response obtained in the monotonic and cyclic tests. From the results obtained in the experimental program, the following conclusions can be pointed out:

1. The nonlinear branch before the peak pullout force increased with Lb;
2. The peak pullout force increased with Lb;
3. The bond strength ranged from 10 MPa to 14 MPa, with a tendency to decrease with an increase of Lb;
4. The ratio between the maximum tensile stress in the CFRP laminate and its tensile strength increased with Lb;
5. The loaded end slip at peak pullout force showed a tendency of a linear increase with Lb;
6. The envelop of the pullout force-slip relationship of the cyclic tests was similar to the curve obtained in the corresponding monotonic test;

7. A continuous decrease of the peak pullout force was observed in the unloading/reloading cycles carried out before the test peak pullout force. The test peak pullout force, however, was not affected by this effect;
8. In the unloading branches of the loading cycles performed in the post-peak regime, no slip at the free end was recovered;
9. The stiffness (i.e., average cyclic inclination) up to the peak pullout force was decrease with the cycle loading. At the initiation of the softening phase the stiffness increased slightly, followed by a smooth decrease.

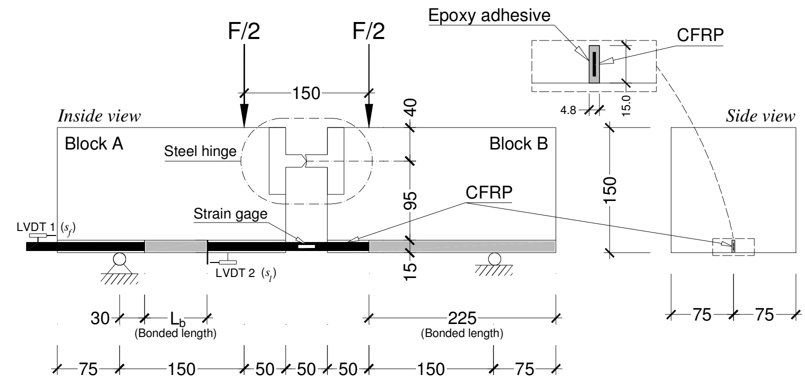

Figure 2: Specimen geometry and pullout-bending test configuration.

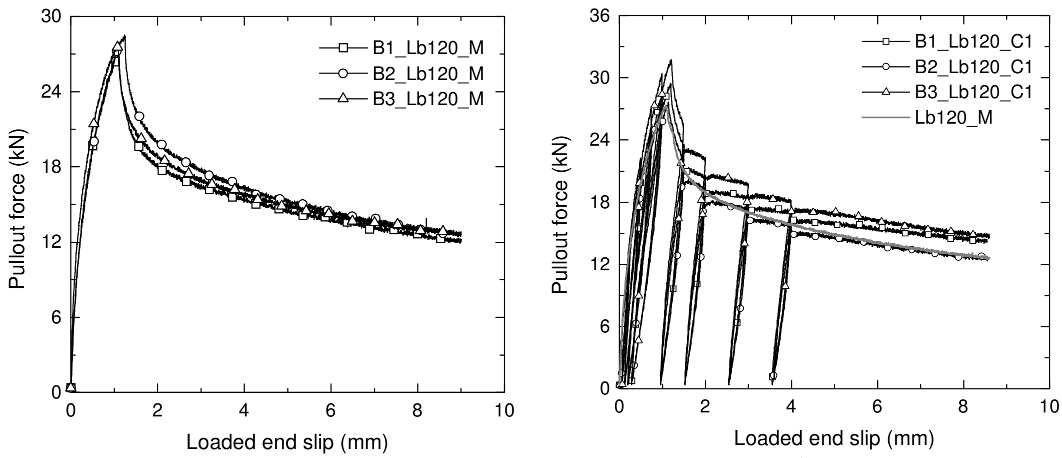

Figure 3: Pullout force *vs.* loaded end slip of the Lb120_M series (a) and Lb120_C1 series (b).

3 ANALYTICAL MODELING OF BOND BETWEEN CFRP AND CONCRETE

The slip of CFRP (s) bonded into concrete is governed by the following differential equation (Sena-Cruz and Barros [14]):

$$\frac{d^2 s}{dx^2} = \frac{2}{t_f E_f} \tau(s) \quad (1)$$

where E_f and t_f are the Young's modulus and the thickness of the CFRP, respectively, and τ is the bond stress acting on the contact surface between CFRP and epoxy-adhesive in the length of dx. The local bond stress-slip relationship consists of the following two eqns:

$$\tau(s) = \tau_m \times \left(\frac{s}{s_m} \right)^{\alpha}, \; if \;\; s \le s_m \quad (2)$$

and

$$\tau(s) = \tau_m \times \left(\frac{s}{s_m} \right)^{-\alpha'}, \; if \;\; s > s_m \quad (3)$$

where τ_m and s_m are the bond strength and its corresponding slip, and α and α' are parameters defining the shape of the curves. This law has been selected for its simplicity and ability to simulate the phenomena under discussion.

Using the slip at the free end, the slip at the loaded end and the pullout force values obtained from the pullout bending tests, a numerical strategy described elsewhere (Sena-Cruz and Barros [14]) was developed in order to determine the values of τ_m, s_m, and α and α' of eqns (2) and (3) that fit, as much as possible, the differential eqn (1). The efficacy of the numerical strategy is well demonstrated in the Figure 4.

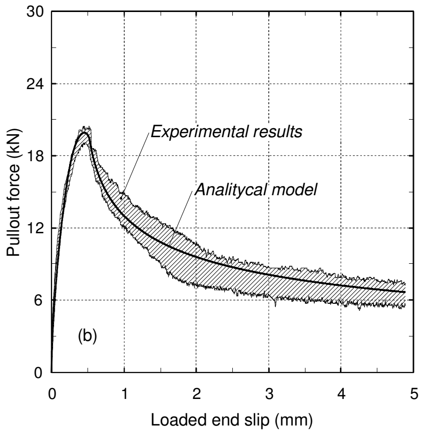

Figure 4: Analytical and experimental results using the analytical model.

4 FEM MODELING OF BOND BETWEEN CFRP AND CONCRETE

Under the finite element frame work the bond behavior between concrete and reinforcing systems is usually simulated by interface elements (Schellekens [10], Rots [15]). A line interface element was implemented in the FEMIX computer code where several types of elements and nonlinear material models can be selected to simulate the behavior of reinforced concrete structures [16]. The pullout-bending test is considered a plane stress problem. The CFRP is simulated by 2D frame elements. Linear elastic behavior is assumed for these materials, having their properties been taken from the experimental program. To connect the CFRP to concrete, four-node line interface elements with two point Lobatto integration rule were used. The bond stress-slip relationship obtained in previous section was used to model the tangential stiffness of the interface element. The obtained results will be published in the full paper corresponding to the present extended abstract.

REFERENCES

[1] Ferreira, D.R.S.M. "Pilares de Betão Armado Reforçados com Laminados de Fibras de Carbono (Reinforced concrete columns strengthened with CFRP laminates)." *MS Thesis*, Civil Engineering Department, University of Minho, Portugal, 2000 [in Portuguese].

[2] Barros, J.A.O., Fortes, A.S. "Concrete beams reinforced with carbon laminates bonded into slits." *Proceedings of 5º Congreso de Métodos Numéricos en Ingeniería*, Madrid, Spain, 16 pp., 2002.

[3] Fortes, A.S., Barros, J.A.O. "Desempenho de três técnicas de reforço à flexão de vigas de betão armado com CFRP (Performance of three CFRP strengthening techniques for RC beams)." *Proceedings of the Conference Betão Estrutural 2002*, Lisbon, 233-242, 2002 [in Portuguese].

[4] Sena Cruz, J.M., Barros, J.A.O., Gettu, R. "Bond behavior of near-surface mounted CFRP laminate strips under monotonic and cyclic loading." *Report No. 04 DEC/E-04*, Department of Civil Engineering, University of Minho, Guimarães, 55 pp. 2004.

[5] Larralde, J., Silva-Rodriguez, R. "Bond and slip of FRP rebars in concrete." *ASCE J Mater Civil Engng*, 5(1), 30-40, 1993

[6] Malvar, L. "Tensile and bond properties of GFRP rein-forcing bars." *ACI Mater J*, 92(3), 276-2985, 1995.

[7] Cosenza, E., Manfredi, G., Realfonzo, R. "Behavior and modeling of bond of FRP rebars to concrete." *ASCE J Compos Construct*, 1(2), 40-51, 1997.

[8] Focacci, F., Nanni, A., Bakis, C.E. "Local bond-slip relationship for FRP reinforcement in concrete." *ASCE J Compos Construct 2000*, 4(1), 24-31, 2000.

[9] De Lorenzis, L., Rizzo, A., La Tegola, A. "A modified pull-out test for bond of near-surface mounted FRP rods in concrete." *Elsevier*, Composites Part B, 33(8), 589-603, 2002.

[10] Schellekens, J.C.J. "Computational strategies for composites structures." *PhD Thesis*, Delft University of Technology, 1992.

[11] Henriques, A.A., Costeira, S.P., Oliveira, L. "Computational modeling of the nonlinear behaviour of concrete structures strengthened by FRP." *Proceedings of the International Conference Composites in Construction - CCC2001*, 629-634.

[12] De Lorenzis, L. "Strengthening of RC structures with near-surface mounted FRP rods." *PhD Thesis*, University of Lecce, Italy, 2002.

[13] RILEM. "Bond test for reinforcement steel. 1. Beam test." *TC9-RC*, 1982.

[14] Sena-Cruz, J.M., Barros, J.A.O. "Modeling of bond between near-surface mounted CFRP laminate strips and concrete." *Computers & Structures*, ELSEVIER, 2004 [Article in Press].

[15] Rots, J.G. "Computational modeling of concrete fracture." *PhD Thesis*, Delft University of Technology, 1988.

[16] Azevedo, A.F.M., Barros, J.A.O., Sena-Cruz, J.M., Gouveia, A.V. "Software no ensino e no projecto de estruturas (The use of software in the structural design and research)." *III Luso-Moçambicano Conference*, Mozambique, 81-92, 2003 [in Portuguese].